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The Future of University Nuclear Science & Engineering Programs

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United States: Facing a Defining Moment of Energy Choices

Chairperson Biggert, members of the Subcommittee on Energy, and other invited guests, thank you for this opportunity to appear before you today to provide testimony on the university capacity to educate and innovate to meet the challenges of our nuclear energy infrastructure. I am a professor in the Energy and Resources Group, the Goldman School of Public Policy, and the Department of Nuclear Engineering at the University of California, Berkeley. I am also the founding director the Renewable and Appropriate Energy Laboratory. From 2000 – 2002 I served on the Subcommittee for Generation IV Technology Planning of the Nuclear Energy Research Advisory Committee (NERAC). This subcommittee, also referred to as the Generation IV Roadmap NERAC Subcommittee (GRNS), was formed in October 2000 to provide advice to the Director, Office of Nuclear Energy, Science and Technology of the U. S. Department of Energy on the development of the Generation IV Roadmap. GRNS was also tasked with developing the technology goals for Generation IV nuclear energy systems. I am the co-author of *Should We Risk It*, an instructional text on technical, social, and policy aspects of risk management. I serve as a board member of The Utility Reform Network (TURN). I am Fellow of the American Physical Society, and have served on American Academy of Arts and Sciences' Committee on the Social Impacts of Technology (Section X).

The United States faces a significant number of technological, economic, environmental, and strategic issues and options surrounding the future evolution of our energy infrastructure. These questions include the mix of fossil-fuel, nuclear, renewable energy, and energy efficiency measures that the U.S. will support, the degree of environmental damage that we will implicitly or explicitly permit to take place as a result of our energy choices, the overall role of innovation and global energy leadership that the U. S. will assume, and our commitment to a transition to a more sustainable and socially desirable energy infrastructure. Most of these questions have not received sufficient examination, even with the increased attention that energy issues have recently commanded at the state, federal, and international levels.

The role of nuclear energy in the current and future mix of energy technologies, markets, and risks is of major importance to the overall energy strategy that we will pursue. The role of nuclear power, specifically the impacts, economics, and risks of the full nuclear fuel cycle, is arguably one of the most challenging energy policy issues facing the country.

In this testimony I will address a number of points that must be addressed if we are to develop and implement a reasoned and diverse sustainable energy strategy for the United States. In this testimony, specifically regarding nuclear power I will comment on:

- The current status of the U. S. nuclear energy industry and its relationship to the rest of our energy resource base;
- The university capacity to manage the current and future nuclear energy infrastructure; and,
- The areas where federal attention is most critically needed to evaluate and plan for our future energy infrastructure.

Finally, I will provide a set of recommendations that I believe are critical if nuclear energy is to be evaluated in the wider context of national energy choices and international energy leadership.

Overview of the Nuclear Industry/University Status

The commercial nuclear industry in the United States has undergone dramatic changes over the past decade. In the following two sections, I sketch that evolution.

Signs of Decline

Many of the trends during the early 1990s were particularly negative for the industry. A decade ago the number of operating nuclear plants was declining as new shut-down announcements were made almost every year, undergraduate and graduate enrollments were declining, and a significant number of university programs were headed for closure. In addition, the busbar cost of electricity generated from nuclear plants was climbing. This trend was in stark contrast to that seen for virtually every other energy technology where the costs have been declining according to a predictable pattern. For most power systems the costs have been seen to decline by 10 – 20% for each doubling of installed capacity. Photovoltaics, biomass power plants, wind turbines, and gas turbines, for example, have each been well studied, and follow this relationship particularly well. This trend, known as a *learning curve* is well understood for technologies that can be mass produced[1], and has been used to forecast the future cost declines for wide range of energy technologies[2]. U. S. nuclear power plants are largely unique, 'one-off' facilities, and thus not expected *even theoretically* to exhibit significant learning-based cost declines. The future of nuclear power is further complicated by issues of waste management, proliferation resistance, and in many areas, strong public skepticism. The university impact of these forces can be seen

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[1] PCAST (President's Committee of Advisors on Science and Technology) (1997) 'Federal Energy Research and Development for the Challenges of the Twenty-First Century', Washington, D.C., Energy Research and Development Panel, President's Committee of Advisors on Science and Technology.

[2] Duke, R. D. and Kammen, D. M. (1999), "The economics of energy market transformation initiatives", *The Energy Journal*, **20**: 15 – 64.

in Figure 1, which highlights the decline in enrollment by new undergraduates at five leading nuclear engineering programs in the United States.

Enrollment decline is particularly serious for the industry, which is already concerned with the aging of the field, in part because university resources as well as those from federal agencies decline with lower enrollment levels, creating a negative feedback loop that can reduce, innovation and resources. This problem became even more severe: the closing or curtailment of of over one-third of U. S. nuclear engineering programs between 1991 and 1998. These changes have been well described in a 2000 report on *The Future of University Nuclear Engineering Programs and University Research & Training Reactors.* This excellent analysis, known widely as the 'Corrandini report' found among other things that there was[3]:

- A serious decline of nuclear science and engineering personnel, the relevant technical facilities and the needed institutional support for each of them;
- A growing imbalance between the supply of qualified personnel and the demand;
- A persistent lack of effective communication with the public, both technical and non-technical, which leads to public opinion based on incomplete information (page 7).

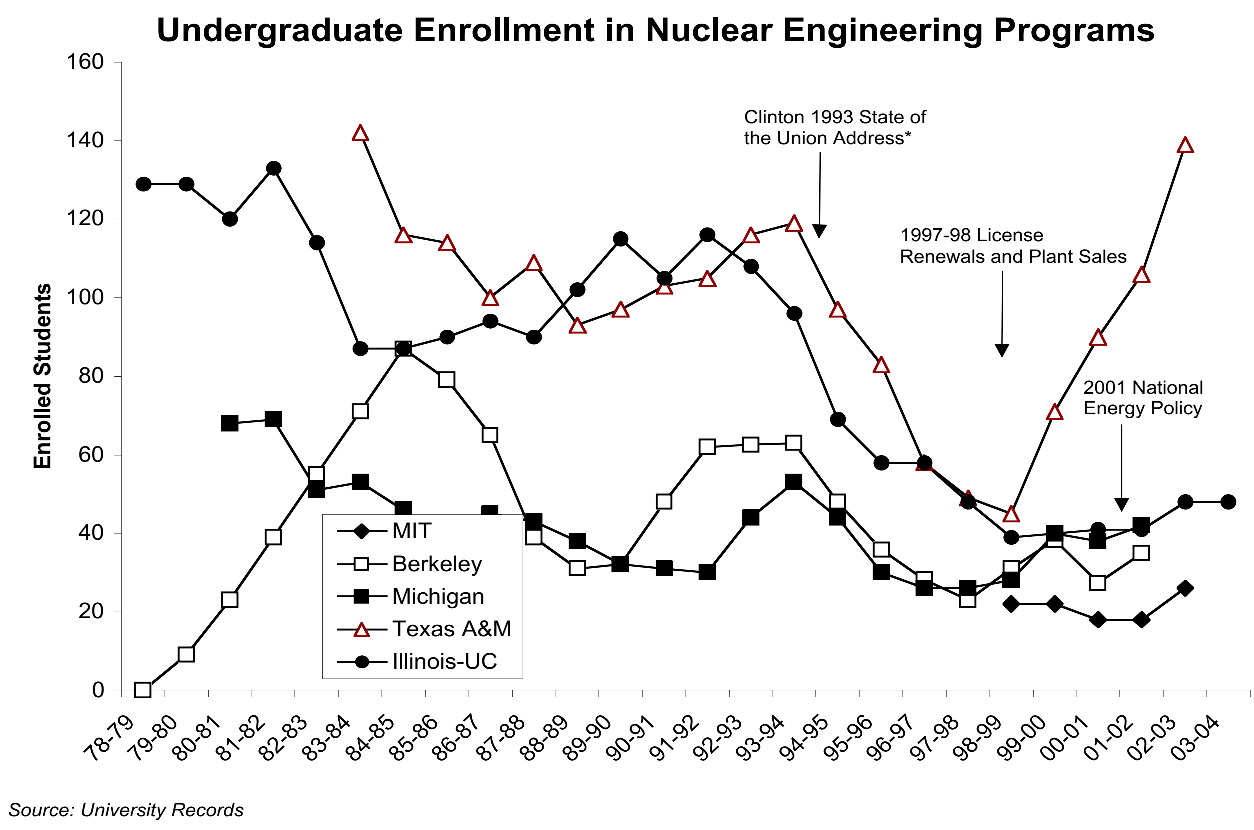

Figure 1: First year undergraduate enrollment in nuclear engineering programs at three leading universities, with pointers indicating seminal policy events during this period, 1978 – 2003. Texas A&M, which engaged in a significant faculty and resource expansion, is a notable exception.

[3] Corrandini, M. L. *et al.*, (2000) *The Future of University Nuclear Engineering Programs and University Research & Training Reactors.*

Figure 1 also illustrates the dramatic importance of policy direction and leadership to the nuclear industry. The statement by President Clinton in his 1993 State of the Union Address that nuclear energy will be largely removed from U. S. energy policy, coupled with the lack of any clear prospects for new nuclear reactors, led to a dramatic decline in enrollment in nuclear science and engineering departments. By the same token, the new emphasis that nuclear power is receiving under the current Bush administration has contributed to a resurgence in the industry. In both these negative and positive phases high-level policy leadership is clearly a vital factor in the direction and vitality of the industry and the academic departments.

Graduate enrollment trends during this period remained more stable (Figure 2), but this is, in fact deceptive. While overall enrollment has not changed significantly, the composition of the graduate nuclear engineering pool shifted during the past decade. At the University of California, Berkeley, foreign students comprised less than 20% of full-time doctoral enrollment in 1994, while in 2000 foreign students accounted for almost 70% of the student population. This trend has taken place in departments across the country to varying degrees although has lessened and at some universities reversed since September 11, 2001.

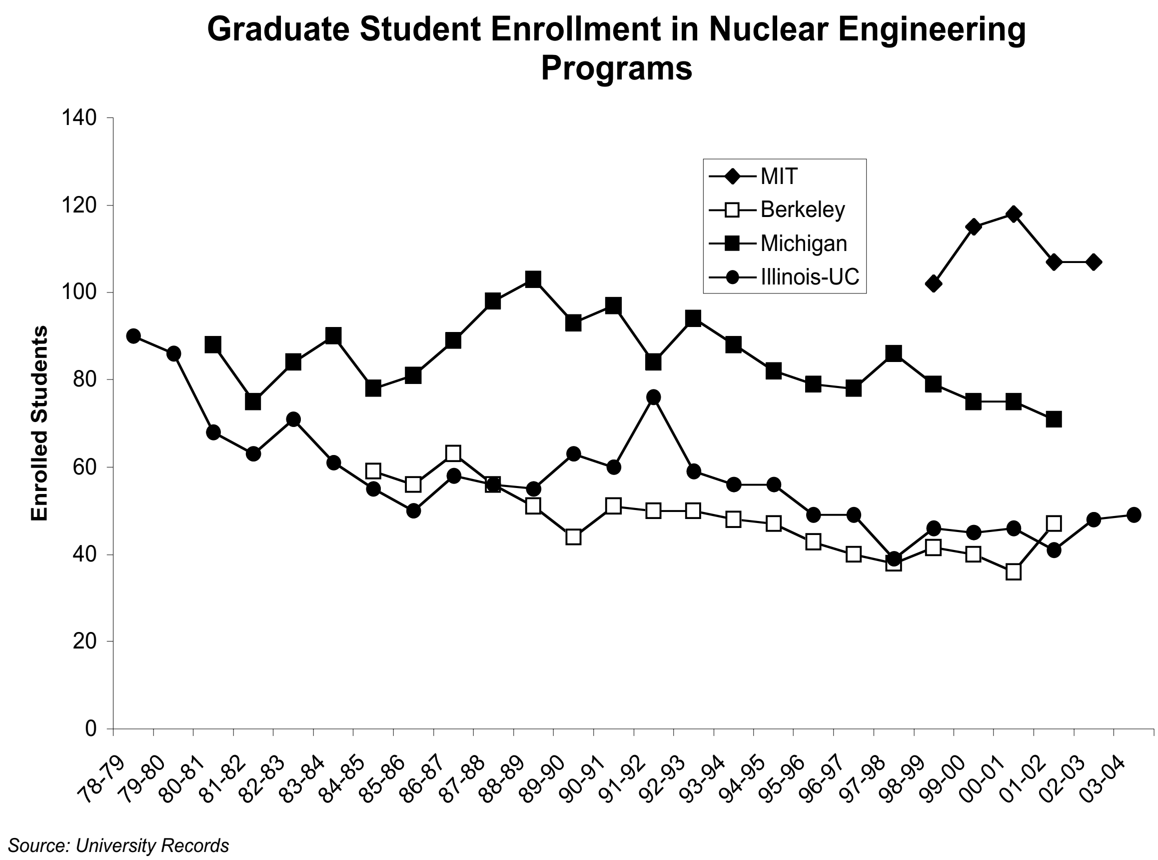

Figure 2: Graduate enrollment in four leading nuclear engineering programs, 1978 – 2003.

In the mid-1990s many of the proponents of nuclear power saw Asia as the primary market for growth, both in terms of new plant construction and as a region of nuclear economic viability.

Signs of Growth

Over the last several years the situation in the nuclear industry has changed dramatically. U. S. nuclear power plants have increased their *capacity factor*, defined as the percentage of time during the year that the plant is available for electricity generation, has increased sharply. From a low of roughly 55% two decades ago, the nuclear industry implemented a range of reforms and the capacity factor began to change. A steady improvement in the operation of nuclear power plants was followed in the mid-1990s by an even more rapid upsurge in plant availability. This second phase was driven by in part by changes in the energy industry, where deregulation experiments, and increasing concerns over the impacts of fossil-fuel based plants expanded the market for nuclear-generated electricity.

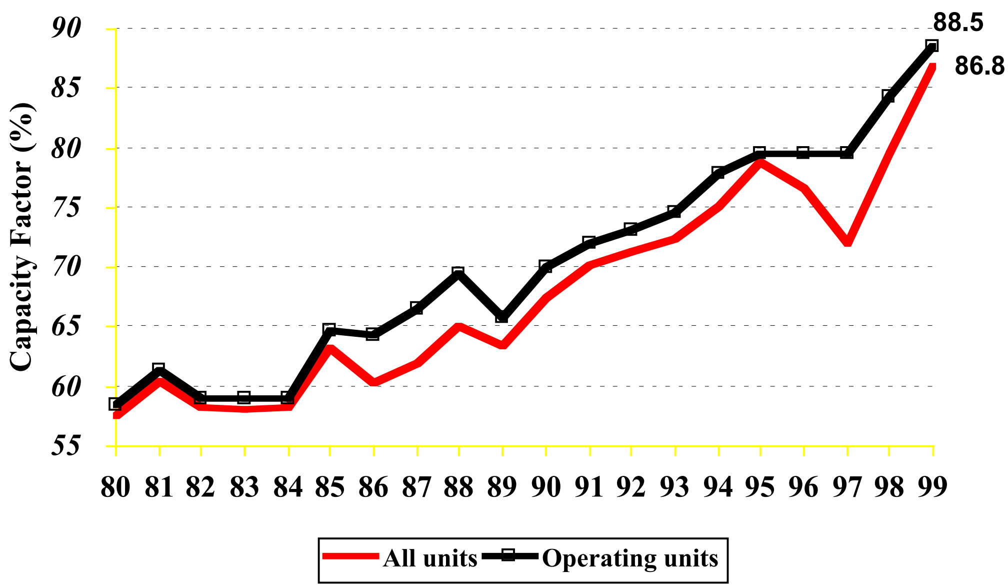

Figure 3: Dramatic change in the capacity factor of nuclear energy facilities, 1980 – 1999.

The impact of this whole-scale change in the industry should not be underestimated. Over the past decade the nuclear industry in the U. S. has added the *equivalent* of over 20 power plants to the national fleet without building a single new facility. In 2000 nuclear power provided 19.8% of total U. S. electricity, or 754 billion kilowatt hours, and in each of the past two years the industry has set new production records.

In addition to the dramatic change in the industry capacity factor, nuclear power plants have gone from readily available on the market for investors, to difficult to impossible to find available for sale. At the same time virtually every U. S. nuclear facility either has, or is expected to apply for re-licensing/license extension. In 2003, nearly half of the nation's 103 nuclear power plants have either renewed their licenses (14 reactors), filed with the Nuclear Regulatory Commission for license renewal (16 reactors), or officially informed the NRC that they expect to apply for license renewal over the next six years (20 reactors). In all, this will increase the life-span of the U. S. fleet of nuclear reactors by roughly 20 years per plant.

The nuclear industry has received a significant boost from efforts such as those of the Nuclear Energy Institute (www.nei.org) to portray the industry as not only the source of low-cost electricity, but also as carbon-free power (Figure 4, below)[4].

The nuclear energy industry has also received arguably the most important support from the current administration which has included nuclear power as part of its core energy strategy.

Industry arguments for nuclear power highlight the low production cost of fission-generated electricity, currently at a little over 2 cents per kilowatt-hour. It is in this area of economics that the complexities of nuclear become most apparent. While pro-nuclear analyses, such as those of the Nuclear Energy Institute, list power costs of 3.8 – 4.8 cents/kWh, nuclear opponents such as Rocky Mountain Institute (www.rmi.org) cite costs of 8 - 12 cents/kWh. Strong arguments can, and are, made for either cost calculation.

In fact, a key issue that must be addressed in evaluating nuclear power is degree to which ideology – either for or against – drives the analysis of cost. The differences in the costs for a variety of nuclear energy related factors are often extreme. The NEI, for example, lists the construction times of 4 – 5 years possible for new nuclear power plants, while RMI quotes the historical construction time of over 10 years per plant, and costs, including overruns of \$2200 – 4,000/kW. NEI cites the initially computed costs of \$1550 – 1880/kW. In perhaps the most egregious example of disagreement, NEI quotes the cost of waste management at 0.1 cent/kWh, while RMI cites the same 0.1 cent/kWh per plant, but then adds an additional 1 cent/kWh more if the cost of Yucca mountain facility is included in the calculation. Similarly, NEI quotes 0.05 – 0.1 cent/kWh for the decommissioning cost (a fee paid into the decommissioning fund) while RMI quotes a cost of 0.4 – 1.0 cent/kWh for decommissioning when events such as the California nuclear bailout (included in the deregulation bill of 1996, AB1890) is included in the cost. These differences reflect an important issue: nuclear energy economics are in many respects not commensurate with those of other energy technologies.

[4] The NEI advertisement series 'Clean air is so 21st Century' also received the 'greenwash' award from CorporateWatch, http://www.corpwatch.org/campaigns/PCD.jsp?articleid=215

If I were to guess, nuclear power is likely to continue to provide *roughly* 20% of our electricity for many years to come. The 'error bars' on this assessment are probably not overly large, on the high side, but could go quite a bit farther on the low side below the 20% middle. This is based on the continuing tension between the pro- and anti-nuclear energy lobbies. The current level represents an uneasy truce where existing facilities continue to operate, with the potential for some new plants, but unlikely to greatly exceed those that must be retired due to age or other factors. A significant increase in the number of nuclear plants is in my view both unlikely due to opposition, and probably unnecessary in light of the growing number of low-carbon alternatives, that include energy efficiency, biomass, wind, and solar energy. Proponents on either side make strong cases for or against nuclear power. A wealth of models exists, of course, that collectively are used to forecast anything from a complete elimination of the industry, to a dramatic expansion of our nuclear fleet. Experts who pretend to have a more precise forecast than this are not being realistic: the extent of our nuclear future is a consequence of policy choices, and is not readily evaluated with deterministic economic models.

University Capacity for Nuclear Energy Training and Innovation

There is a great deal of concern within the nuclear industry and the academic community over the decline in the number of nuclear engineering programs and research reactors in the United States (see, e.g. the Corrandini report; footnote 3). A recent GAO analysis, however, estimated that the number of nuclear engineering graduates would be sufficient to meet the personnel demands of even a 'high growth' scenario (with the U. S. nuclear fleet growing to ~ 110 plants by 2020) even with the current number of academic programs. While the GAO is quick to note that caution that this calculation is fraught with uncertainties – in particular over the number of nuclear engineering graduates that find employment in other fields -- it is consistent with my own estimates and those of several colleagues. The current set of graduate nuclear science and engineering programs in the U. S. is capable of producing 50 – 70 new graduates per year, which would be more than enough to sustain this industry. A separate issue is the necessary number and type of research and training reactors.

In light of this rough calculation, efforts to create significantly more nuclear engineering departments are probably not necessary. A smaller number of departments that are strong in research and teaching will serve the country better than a larger number of diluted, weaker, ones. In fact, nuclear engineering departments already suffer from an important weakness: nuclear science and engineering is not, on average, attracting the best students. There are some outstanding students, to be sure, but even with the recent upturn in the industry enrollments are more or less flat. The current wave of plant re-licensing – while important to the industry, apparently does not provide the excitement to draw in the best students. In fact, nuclear engineering programs are losing students to electrical and computer science departments.

In every field the surest way to attract the best students is to be innovative, daring, and relevant. Some degree of renewal and of new vision is needed. In my service on the Department of Energy's GRNS Committee in the Generation IV process I was troubled to discover that the roadmap process was not overflowing with individuals excitedly discussing radically new reactor concepts, novel ways to dramatically reduce the waste stream, and ideas for how to integrate nuclear energy training more fully into the wider energy infrastructure. The Generation IV mandate was to develop a process for a truly innovative research and development process for the *next generation* of nuclear plants. Instead, it was a very well managed, analytically sound, evaluation of a range of relatively near-term extensions of current plant designs. This is *not* a criticism of the individuals – many of whom are truly outstanding – but it does lead to a recommendation that a top priority should be to identify ways to support highly innovative approaches to nuclear energy investigation. This problem, of course, is generic to research endeavors across the disciplinary spectrum. Reinvigorating the quality and visibility of nuclear engineering programs, more than the quantity of their graduates, needs to be the focus.

In an important example of the need for new approaches, the Gen IV discussions of hydrogen production by nuclear power plants were limited and arguably overly conventional. Over the past five years half of the papers in the field of nuclear hydrogen – a field that could revolutionize both the nuclear energy industry and potentially the U. S. energy system overall – were authored or co-authored by one individual. This researcher, Charles Forsberg of Oak Ridge National Laboratories, is outstanding and has made *major* contributions. However, at the point in history when hydrogen is on the threshold of potentially becoming a major energy carrier for both stationary and vehicle applications, the lack of a diverse research base on the critical issues of nuclear hydrogen production is troubling. Greater analysis of nuclear hydrogen is also a call for greater cross-disciplinary efforts that compare and contrast different avenues for hydrogen energy systems. Is nuclear the best mode of hydrogen generation? How does it compare to wind, photovoltaic, biomass, or biological production pathways? What are the near and long-term costs, and what are the hidden subsidies? How do each of these methods contribute to national energy security and to global climate protection? These are vital questions, and at present they are all under-researched.

Each of these concerns with the university capacity for nuclear science and technology training largely reflects the overly insular nature of many departments and programs. Engineering programs generally are infamous for the packing the schedules of their students so that they have little opportunity to diversify their education. The Accreditation Board for Engineering and Technology (ABET) 2000 process is one mechanism that moves departments to not only offer a wider range or courses themselves, but to broaden the training of students with courses in other engineering *and* non-engineering areas. This is absolutely critical to prevent 'in-breeding' and to challenge students and faculty to think in new, innovative ways. Graduate students in nuclear engineering departments would benefit from this more diverse education. A number of mechanisms exist to support this broader energy education, including:

- Encourage students to obtain masters degrees in a different discipline than their intended Ph.D. field (for example through fellowships or support for added time and flexibility in graduate school)
- Develop a curriculum in 'energy engineering' that schools could consider, and adopt in sum or in part to provide nuclear engineering students and even post-doctoral fellows with a broader energy systems and even energy economics and policy perspective
- Develop university exchange programs, particularly with overseas departments where very different teaching styles exist, and where the nuclear energy industry is very different from that in the U. S.[5]

[5] Nuclear Energy Agency (2000) *Nuclear Education and Training: Cause for Concern?* (OECD: Paris).

An important first step would be to convene a group of U. S. and foreign nuclear energy experts, along with scholars, practitioners, and policy makers from other energy sub-fields to develop a more comprehensive suite of mechanisms that could be implemented to diversify and to add excitement and new modes of innovation to the field.

The Federal Role

The federal government plays the pivotal role in the encouragement of innovation in the energy sector. Not only are federal funds critical, but as my work and that of others has demonstrated[6], private funds generally follow areas of public sector support. One particularly useful metric – although certainly not the only measure -- of the relationship between funding and innovation is based on patents. Total public sector funding and the number of patents – across all disciplines – in the United States have both increased steadily over at least the past three decades (Figure 5).

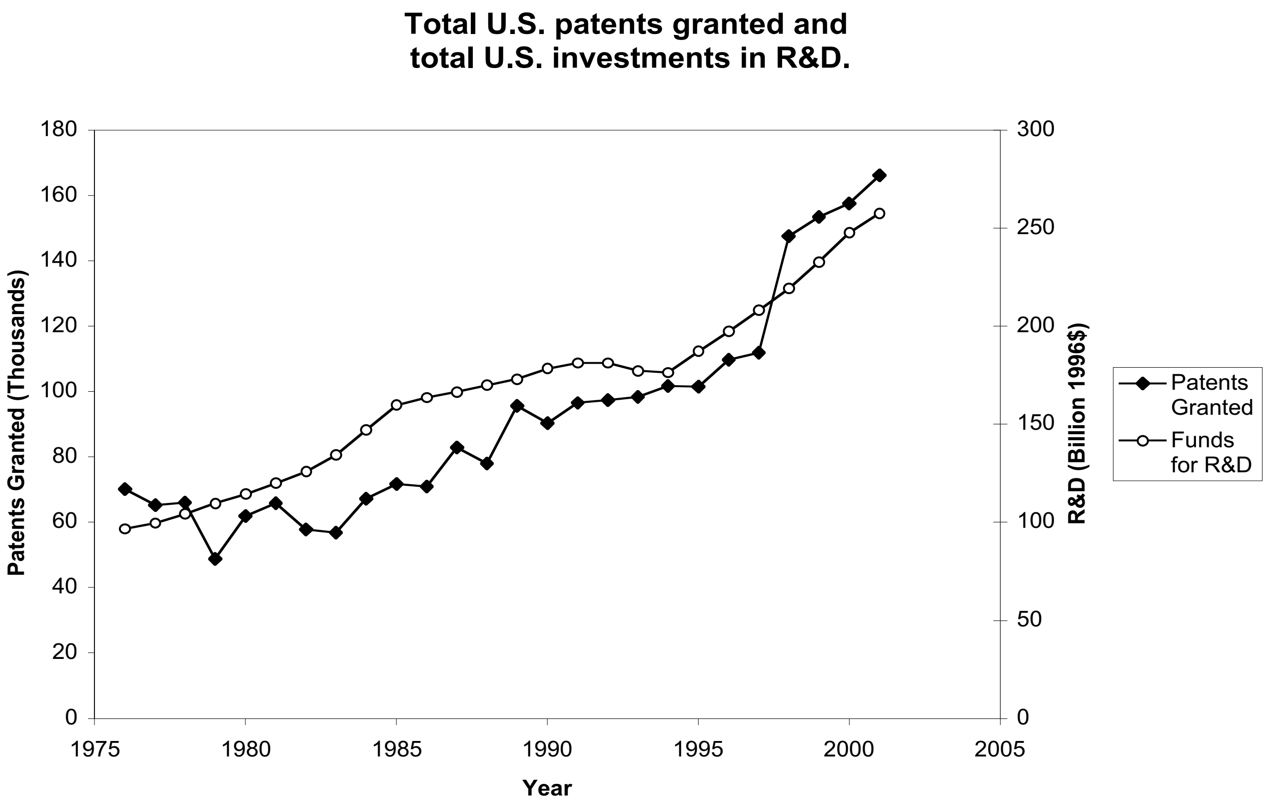

Figure 5: Total public sector spending on R&D (right axis) and total patents (left axis). Figure from Margolis and Kammen (1999) *Science*, **285**, 690 – 692.

The situation depicted here, with steadily increasing trends for funding and results (measured imperfectly, but consistently, by patents) is not as rosy when energy R&D alone is considered. In that case the same close correlation exists, but the funding pattern has been one of decreasing

[6] Margolis, R. and Kammen, D. M. (1999) "Under-investment: The energy technology and R&D policy challenge", *Science,* **285**, 690 - 692.

resources (Figure 6A). Figure 6A shows energy funding levels (symbol: ○) and patents held by the national laboratories (symbol: ♦). The situation need not be as bleak as it seems. During the 1980s a number of changes in U. S. patent law permitted the national laboratories to engage in patent partnerships with the private sector. This increased both the interest in developing patents, and increased the interest by the private sector in pursuing patents on energy technologies. The squares (■) in figure 6 show that overall patents in the energy sector derived from public sector funds increased.

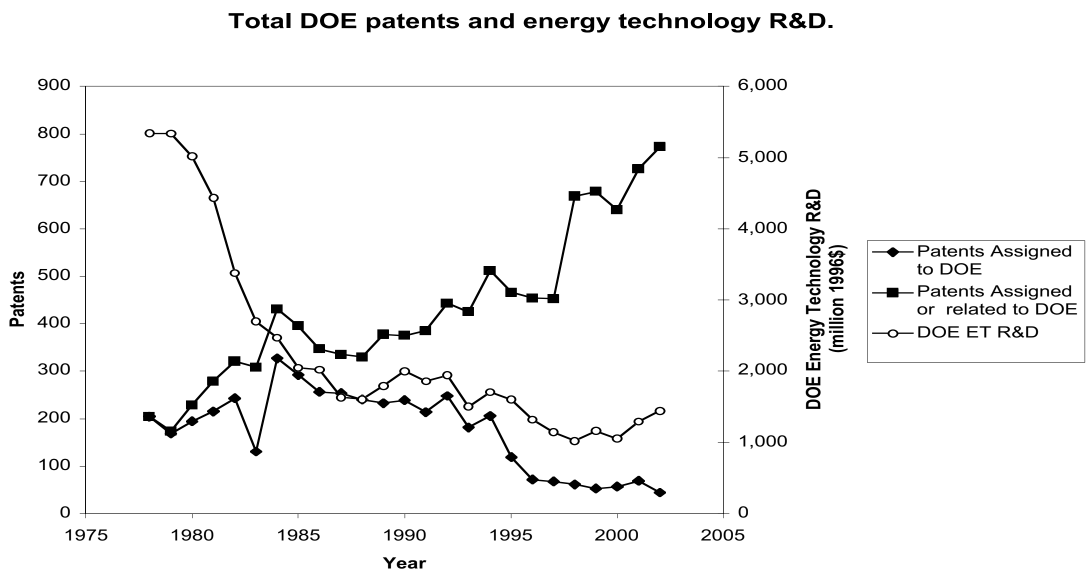

Figure 6A: Public sector R&D funding and patents across all energy technologies, both held and shared by the federal energy laboratories. Figure from Kammen and Margolis[7].

[7] Kammen, D. M. and Margolis, R. (1999) "Evidence of under-investment in energy R&D in the United States and the impact of Federal policy", *Energy Policy*, **27 (10)**, 575-584.

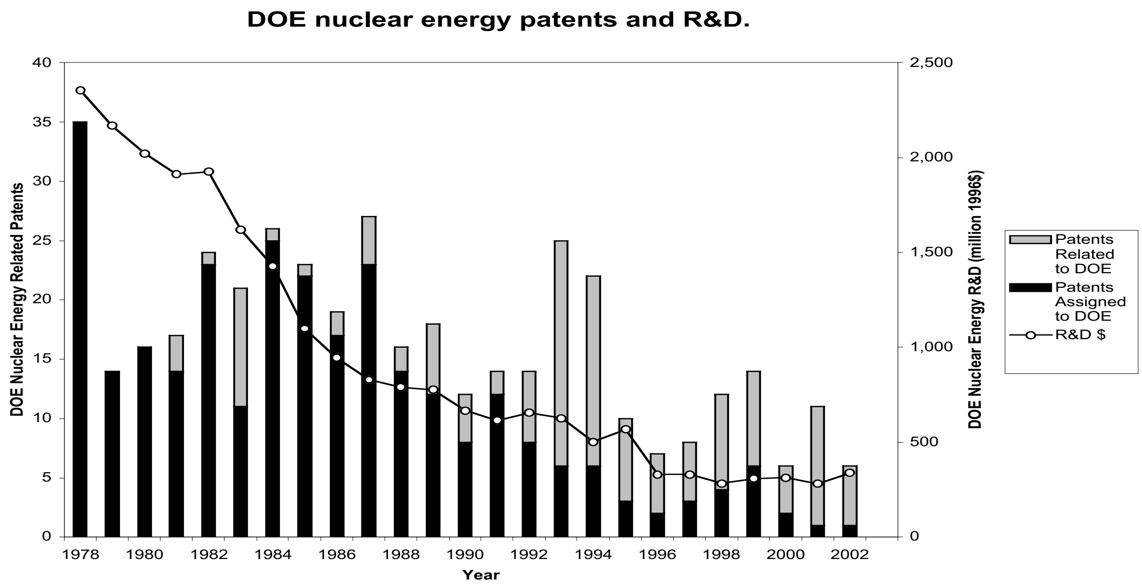

Figure 6B: Nuclear energy funding and patents. Figure from Kammen and Margolis (1999).

Figure 6B reveals that patent levels in the nuclear field have declined, but not only that, public-private partnerships have taken placed (shaded bars), but have not increased as dramatically as in energy field overall (Figure 6A). There are a number of issues here, so a simple comparison of nuclear R&D to that on for example, fuel cells, is not appropriate. But it is a valid to explore ways to increase both the diversity of the R&D. This is a particularly important message for federal policy. Novel approaches are needed to encourage new and innovative modes of research, teaching, and industrial innovation in the nuclear energy field. To spur innovation in nuclear science a concerted effort would be needed to increase the types and levels of cooperation by universities and industries in areas that depart significantly from the current 'Generation III+' and equally, away from the 'Generation IV' designs. Similar conclusions were reached by M. Granger Morgan, head of the Engineering and Public Policy Program at Carnegie Mellon University, in his evaluation of the need for innovative in the organization and sociology of the U. S. nuclear power industry[8].

A second important issue that this Committee might consider is the degree of federal support for nuclear fission relative to other nations. Funding levels in the U. S. are significantly lower than in both Japan and France. Far from recommending higher public sector funding, what is arguably a more successful strategy would be to increase the private sector support for nuclear R&D and student training fellowships. Importantly, this is precisely the sort of expanded public-private partnership that has been relatively successful in the energy sector generally.

[8] Morgan, M. G. (1993) *Environment*, Spring, 1993.

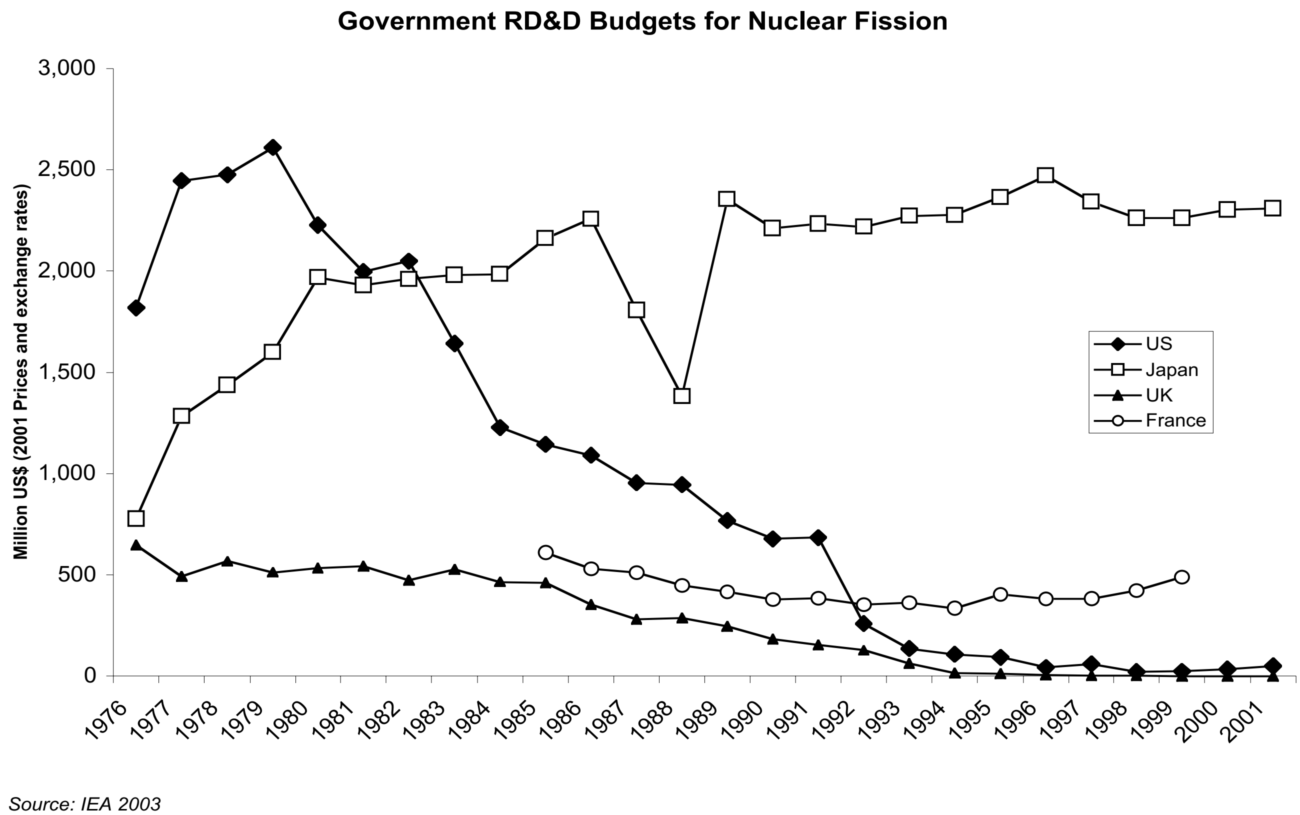

Figure 7: Comparison of government funding levels for nuclear fission, 1978 – 2001.

It is incorrect, however, to think that this is a process that can be left to the private sector. There are key issues that inhibit private sector innovation. As one example, many nuclear operating companies have large coal assets, and thus are unlikely to push overly hard, in areas that threaten another core business.

This emphasis on industry resources used to support and expanded nuclear program – under careful public sector management – has been echoed by a variety of nuclear engineering faculty members:

> *I believe that if you were to survey nuclear engineering department heads, most would select a national policy to support new nuclear construction, over a policy to increase direct financial support to nuclear engineering departments. A firm commitment by the federal government, to create incentives sufficient to ensure the construction of a modest number of new nuclear plants, with the incentives reduced for subsequent plants, would be the best thing that could possibly be done for nuclear engineering education and revitalization of the national work force for nuclear science and technology.*
>
> - Professor Per Peterson, Chair,
> Department of Nuclear Engineering, University of California, Berkeley

Recommendations

In addition to the recommendations listed in the sections of this testimony, two issues stand out for further discussion and action:

- Cross–disciplinary training is critical in the energy field, and is particularly critical for the nuclear power sector, which should be more fully integrated into energy planning and evaluation across a wide range of energy technologies and systems. Nuclear science and engineering departments should be supported and encouraged to provide a more widely interdisciplinary training at both the undergraduate and graduate levels.

- Hydrogen is a particularly important promising future energy carrier. The potential for nuclear power plants to play an important role in a hydrogen future exists, but more, and more diverse, research needs to be conducted on this relationship.

- Nuclear waste and proliferation, despite widespread concern, deserve added attention, particularly as the types of security threats to the U. S. changes. Domestic energy, notably carbon and pollution-free energy sources are critically important to the U. S., and greater emphasis on understanding the full spectrum of these choices – including solar, wind, biomass, geothermal and nuclear – is in the national interest.

- Carbon trading and carbon emissions quotas, and other mechanisms to force companies to measure and value environmental damage, provides one key area where federal attention is needed, and is one area where it is natural to force and expect analysis and innovation across technologies. This would be an important part of an overall clean energy strategy that would include a renewable energy portfolio standard, a system benefits charge, and incentives for innovation[9].

Thank you for your time and consideration, and I welcome the opportunity to discuss these issues at greater length.

[9] Kammen, D. M. (2001) Testimony for the Hearing on 'Technology and Policy Options for Climate Change' for the U. S. Senate Committee on Commerce, Science, and Transportation, July 10 (United States Senate: Senate Committee on Commerce, Science, and Transportation).
URL http://www.senate.gov/~commerce/

Biographical Sketch: Daniel M. Kammen

Daniel M. Kammen received his undergraduate education in physics from Cornell University 1984. He received his Masters (1986) and Doctorate (1988) degrees in physics, from Harvard University. He was a Bantrell & Weizmann Postdoctoral Fellow at the California Institute of Technology, and then a lecturer in the Department of Physics at Harvard University. From 1992 – 1998 Kammen was on the faculty of the Woodrow Wilson School of Public and International Affairs at Princeton University, where he was Chair of the Science, Technology and Environmental Policy Program. Kammen is now Professor in the Energy and Resources Group (ERG), the Goldman School of Public Policy, and in the Department of Nuclear Engineering at the University of California, Berkeley. At Berkeley Kammen is the founding director of the Renewable and Appropriate Energy Laboratory (http://socrates.berkeley.edu/~rael), and is campus representative to the University of California Energy Institute. He has been a Lecturer in Physics and Natural Science at the University of Nairobi, serves on US EPA and DoE review committees, and on study panels of the International Panel on Climate Change.

Kammen's research centers on the science, engineering, economics and policy aspects of energy management, and dissemination of renewable energy systems. He works on the health and environmental impacts of energy generation and use; rural resource management, including issues of gender and ethnicity; international R&D policy, climate change; and energy forecasting and risk analysis. He is the author of over 140 journal publications, five books, including one on environmental, technological, and health risks (*Should We Risk It?* Princeton University Press, 1999) and numerous reports on renewable energy and development. Kammen received the *1993 21st Century Earth Award* and is a Fellow of the American Physical Society. He is a Permanent Fellow of the African Academy of Sciences. He appears frequently in the media as a commentator on energy and environmental issues.

For information of any of these activities, see http://socrates.berkeley.edu/~dkammen and http://socrates.berkeley.edu/~rael.

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I would like to thank Charles Forsberg, William Kastenberg, and Per Peterson for their input on the relationship of university programs and the U. S. nuclear energy industry. The views expressed here are, of course, my own. Greg Nemet, a doctoral student in the Energy and Resources Group provided invaluable research assistance in the preparation of this testimony. Email: gnemet@socrates.berkeley.edu